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LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Life-cycle assessment of continuous pad-dyeing technology for cotton fabrics

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Abstract
Purpose China is the largest producer of textile-dyeing products in the world. The production of these materials consumes high amounts of water and energy and results in the discharge of huge amounts of pollutants. This study aimed at evaluating the life-cycle environmental impacts of the textile-dyeing industry and determining the key processes for mitigating life-cycle environmental impacts efficiently and effectively, which will benefit the application of cleaner production technologies.
Methods A life-cycle assessment was performed according to the ISO 14040 standard series. The system investigated includes the dyeing process and final disposal and the transportation of raw material, energy production, and transportation. The functional unit is 10,000 m of cotton fabric, which weighs 2,000 kg. Our study encompasses three types of data. The data regarding the production process and the major raw materials, necessary energy, and the source of the energy, as well as the emissions of some pollutants, were provided by a textile-dyeing enterprise in Jiangsu Province. The data regarding transport were generated using the GaBi version 4.3 database. Some emission factor data such as those on CO_2, CH_4, and N_2O emissions were obtained from the literature. Resources, energy consumption, and emissions are quantified, and some of the potential environmental effects were evaluated using the CML2001 method built into the GaBi version 4.3 database.
Results and discussion Scouring and oxygen bleaching, dyeing, stentering and setting, wastewater treatment, and incineration are the key processes in terms of global warming potential, acidification potential, photochemical ozone creation potential, and eutrophication potential. It will therefore be useful to enhance the recycling of water, control the consumption of additives and dyes, and conserve energy as much as possible. Through scenario analysis, we note that motorized shipment should be used instead of shipment by trucks, when conditions permit.
Conclusions To promote energy conservation and the clean production of continuous pad-dyeing technology for cotton fabrics, other environmental impact categories besides the impact of the water system should be given focus. Additional work can be performed on the following: considering a consumption-based perspective of the entire process, uncertainty in data on life-cycle inventory, the evaluation methodology employed, temporal and spatial variation, the normalized toxicity of dyes and additives, and weighting methods.

Keywords Cleaner production · CML2001 · Cotton fabric · GaBi · Life-cycle assessment · Pad dyeing

1 Introduction

Textile-dyeing products greatly affect people's daily lives. As the largest contributor of textile-dyeing products in the world, the textile-dyeing industry in China produced 60.603 billion m of fabric in 2010, contributing more than 40 % (Inknet.cn 2011) of the total world production.

Traditional textile dyeing is typically a heavy-polluting and labor-intensive industry that consumes a large amount of water and energy. The textile-dyeing industry consumed 9.548 billion tons of water in 2010, the second highest water consumption for all industries. Furthermore, traditional textile dyeing generates high amounts of wastewater, of which

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only 7 % is recycled in 2010 (Wang et al. 2011). These effluents are characterized by the presence of BOD, chemical oxygen demand (COD), toxic substances (including metals and dyes), and volatile organic compounds (VOCs), which all have severe impacts on the environment (Ibrahim et al. 2008). Simultaneously, the annual energy consumption of this industry is 68.67 million tons of standard coal, three times the amount of energy consumed by this industry in developed countries. The energy efficiency of this industry is only approximately 35 %. Globalization, intense international competition, and a lack of ecological balance are currently affecting this sector adversely. These considerations demand a focus on resource conservation and environmental management for the textile-dyeing industry (Baban et al. 2010; Tanapongpipat et al. 2008).

Resource conservation and environmental management for the textile-dyeing industry have so far been concerned mainly with improving technology and equipment (Hou et al. 2010), low toxicity and low pollution levels for raw materials (Moore and Ausley 2004; Tang 2006; Xie et al. 2011), and intelligent optimization of order scheduling (Jiang et al. 2010; Sun et al. 2010), as well as wastewater recycling and end treatment (Chen 2008; Lu et al. 2009). Current research mainly focuses on reducing the impact of the production process on water, thus overlooking other environmental impacts such as impacts on the atmosphere as well as the integrated impacts of other processes involved in textile dyeing such as energy production and the transportation of raw material. The scope of the current research will not be able to cover and control all of the environmental impact categories of the entire life cycle of the textile-dyeing industry efficiently (Hicks and Dietmar 2007). Increased awareness of the importance of environmental protection and the possible impacts associated with the products has increased interest in the development of methods to better understand and address these impacts. Consequently, recognition of the most prominent environmental impacts as well as the generation phase of the industry is the key to sustainable development in the textile-dyeing industry.

Life-cycle assessment (LCA) addresses all of the potential environmental impacts throughout a product's life cycle, from raw material acquisition through transportation, production, use, and end-of-life treatment (Rivela et al. 2004). LCA has been used to evaluate the environmental impacts of and make recommendations for the food industry (Koroneos et al. 2005; Contreras et al. 2009), the metal-production industry (Norgate et al. 2007), the cement industry (Zhu et al. 2006; Huntzinger and Eatmon 2009), the automobile industry (Puri et al. 2009), the chemical industry (Huijbregts et al. 2000), the semiconductor industry (Liu et al. 2010), and many others. Some LCA studies have also been done on textiles-dyeing industry (Hansen et al. 2007; Nieminen et al. 2007). Thus, it is necessary to address the environmental aspects and potential environmental impacts of the textile-dyeing industry in China.

In the entire textile industry, the dyeing process is the most important in terms of high added value and technical complexity (Jiang et al. 2010). The two main methods for dyeing fabric are impregnating and padding. In China, almost 80 % of the industry's dyed cotton fabrics rely on the continuous padding process (GlobalTextiles 2009). In the continuous padding process, wet processing is the most significant textile operation, which produces large volumes of chemical-laden wastewater. Thus, in terms of wastewater generation and environmental impact, wet processing is important to consider (Ibrahim et al. 2008). Indeed, the wet processing of continuous pad dyeing is a representative technology and has been determined to have tremendous potential regarding cleaner production. We applied the LCA method to evaluate the wet-processing portion of the continuous padding dyeing process and select cotton fabric to be the subject investigated because cotton fabric accounts for a large portion of textile products.

In this paper, we first present an analytical framework based on LCA to determine the life-cycle inventory (LCI) of the continuous pad-dyeing process, which includes dyeing, final disposal and transportation of raw materials, energy production, and transportation. Each process includes several stages, and transportation occurs throughout the entire life cycle. With the help of the GaBi version 4.3 database platform, we selected the CML2001 method to evaluate the LCI of the application of continuous pad-dyeing technology to cotton fabric. We considered nine main impact categories based on the results of LCI, life-cycle impact assessment (LCIA), and ISO 14040. Next, we noted the main impact categories and the key points regarding resource conservation and environmental management in each category. Finally, we devised an optimization proposal for this system and determined the limitations of our study and potential improvements that could be made.

2 Methodology

This study was seriously conducted in accordance with ISO 14040 (2006): Environmental Management-Life Cycle Assessment-Principles and Framework (ISO 14040 2006). However, the procedure was only reviewed and confirmed by our researchers and not certificated by any critical review.

2.1 Goal definition

The main goal of the case study was to identify key issues associated with the life cycle of the wet processing of cotton fabric in the continuous padding-dyeing process. A

secondary goal was to provide decision makers with suggestions on applying cleaner production technologies of energy conservation, emission reduction, and the sustainable development to the entire textile industry. The aims of this study were as follows:

- To determine the pollutant-emission stages and stages that consume large amounts of water and energy by evaluating the life-cycle stages that give rise to the need for most resources and energy inputs and output flows and cause the most significant environmental impact. These stages are the key processes to apply cleaner technologies for energy conservation and emission reduction
- To propose suggestions for resource conservation and the environmental management of wet processing

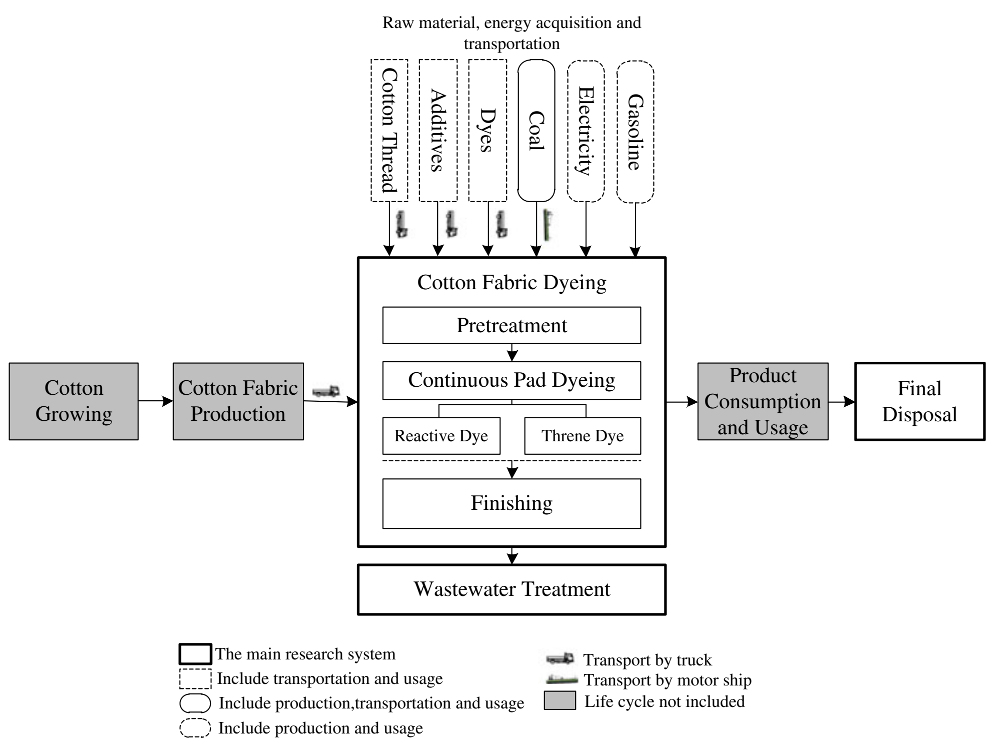
2.2 System boundaries

We mainly considered the dyeing process, final disposal and transportation of raw materials, energy production, and transportation. The dyeing process is subdivided into pretreatment, continuous pad dyeing, and finishing stages. The pretreatment stage includes sewing, cold piling, desizing, scouring and oxygen bleaching, singeing (also called gassing, it is a process applied to both yarns and fabrics to produce an even surface by burning off projecting fibers, yarn ends, and fuzz, which is accomplished by passing the fiber or yarn over a gas flame or heated copper plates at a speed sufficient to burn away the protruding material without scorching or burning the yarn or fabric), mercerizing (a chemical treatment applied to cotton fibers or fabrics to permanently impart a greater affinity for dyes and various chemical finishes. Mercerizing also gives cotton cloth increased tensile strength, greater absorptive properties, and, usually, a high degree of luster), brushing, full-width washing, and baking. In the continuous pad-dyeing phase, we consider two types of dyes, reactive dyes and threne dyes. Finishing includes stentering and setting as well as preshrinking. We must also consider the wastewater treatment stage of the dyeing process, and transportation is necessary throughout the entire life cycle. The cotton-growing and fabric production stages are not considered to fall within the system boundary of this research. However, due to the possible environmental impacts of pesticide use for growing cotton, the cotton-growing stage should be included in future studies. The products are sold mostly for domestic use and are also sold in Southeast Asia for further processing, which involves the problem of transnational allocation of environmental responsibility. Furthermore, the usage stage is assumed to produce little pollution, and therefore, we ignore the product consumption and usage stage. The ultimate system boundary is shown in Fig. 1.

2.3 Functional unit

The functional unit is dyeing of 10,000 m of cotton fabric, which weighs 2,000 kg.

Fig. 1 System boundary of our research



2.4 Data collection and LCI analysis

Our study includes three types of data. The data regarding the production process and the major raw materials, energy, and the source of the energy, as well as the emissions of some pollutants, were provided by a textile-dyeing enterprise in Jiangsu Province. We used the enterprise's data because of the following: (1) the company uses wet processing in continuous pad dyeing; (2) this company integrates research, cultivation, manufacturing, design, sales, and customized services into its business scope and was therefore invited to participate in the Global Green Enterprise Development Forum as the only Chinese company; (3) the company has built partnerships with many internationally renowned manufacturers, and its products and technologies are representative of the industry as a whole; and (4) we have conducted related research on the company for a few years and have a good relationship with the company, which made the data accessible. The data regarding transport tools were constructed using the GaBi version 4.3 database. Some emission factors such as those on carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions were obtained from the literature. The data required to construct a complete LCI were obtained as follows:

1. Transportation and cotton fabric dyeing. The data required for this section include the consumption of resources and energy and the emission of pollutants as well as the allocation of resources, energy, and emissions. Data on the input and output of resources in each stage were obtained by consulting engineers. The following three aspects provide detailed information on energy consumption, allocations, and emissions.

(a) Energy consumption and emissions. The energy used includes electricity and coal (caloric value 4,500 kcal/kg). Gasoline is heated in a heat-conducting oil boiler and is circulated throughout the pipes of the processing machinery, which requires high operating temperatures. There is almost no loss of gasoline in this system because gasoline is regarded as a heat conductor rather than a fuel. We considered the resources, energy consumption, and emissions from the gasoline-production process. Regarding electricity, the phase of electricity use does not discharge pollution; the materials, energy consumption, and emissions arising from the production process are shown in Table 1 (Yang et al. 2002). Each piece of equipment features an electric kilo-water-hour meter so that the consumption of electricity at each stage of the process can be measured easily. In the continuous pad-dyeing stage, the energy used with respect to reactive dyes represents 47 % of the total energy consumption. However, the situation regarding coal is more complex. Coal is used in two types of boilers, a steam heating boiler and an oil heating boiler. The steam heating boiler heats water to produce steam, while the oil heating boiler heats gasoline to generate high temperatures to process cotton fabric. It is necessary to distinguish the stages that require steam and high temperatures; coal must then be allocated to the appropriate corresponding stages. Simultaneously, the inputs and outputs calculated within the production and use processes (resources, energy consumption, and emissions from coal production) are shown in Table 2 (Yang et al. 2002). In our research, the stages that use steam include scouring and oxygen bleaching, mercerizing, brushing,

Table 1 Consumption and emissions for production of 1 MJ of electricity

Input	Quantity	Output		Quantity (mg)
Raw coal	0.327 MJ	Emissions to air	Dust	2.65E+03
Washed coal	0.81 MJ		CO_2	3.17E+05
Fuel oil	6.98E−03 MJ		SO_2	2.87E+02
Crude oil	2.10E−03 MJ		NO_x	2.13
Diesel	9.60E−03 MJ		CO	1.17
Coke oven gas	1.28E−02 MJ	Emissions to water	COD	0.531
Natural gas	1.64E−04 MJ		Pb^{2+}	2.57E−02
Water	1.56E−02 kg		Hg^{2+}	5.40E−04
			F^-	4.86E−03
			SS	54.8
			Cd^{2+}	9.53E−04
			Arsenic	4.72

1 kwh = 3.6 MJ. 1 TJ = 10^6 MJ. The heating value of each type of energy is as follows: raw coal, 20,908 kJ/kg; washed coal, 8,363 kJ/kg; fuel oil, 41,816 kJ/kg; crude oil, 41,816 kJ/kg; diesel, 42,652 kJ/kg; coke oven gas, 17,354 kJ/m^3; natural gas, 38,931 kJ/m^3. The density of coke oven gas and natural gas is 0.4849 kg/Nm^3 and 0.7143 kg/Nm^3, respectively

SS suspended solid

Table 2 Consumption and emissions for production of 1 MJ of coal

Input	Quantity	Output		Quantity (mg)
Electricity	4.77E−03 MJ	Emissions to air	Dust	3.54
Water	0.08 kg		CO_2	895
			CO	1.17
			SO_2	8.573
			CH_4	473
			NO_x	2.13
		Emissions to water	SS	0.762
			COD	0.531

Table 3 Energy consumption and emissions for production of 1 MJ of gasoline

Input	Quantity	Output		Quantity
Energy consumption	0.09 MJ	Emissions to air	CO_2	6 g
			CO	0.63 mg
			NO_x	16 mg
			SO_2	6.5 mg
		Emissions to water	VOC	190 mg

The heating value of gasoline is 43,070 kJ/kg, and its density is 0.73 kg/L

full-width washing, baking, and continuous pad dyeing. The allocation ratio of steam consumption with respect to these processes is 2:1:1:1:1:2, respectively. The stages that require high temperatures include singeing and stentering and setting. The allocation ratio of coal consumption is 1:1. The CO_2 emissions factor for the use of coal is 0.748 kg C/kg according to the greenhouse gas control project of the State Environmental Protection Administration of China (Meng 1997). The emissions of CH_4 and N_2O are calculated according to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC 2006) based on Eq. (1). The individual emission factors are 1 and 1.5 kg/TJ, respectively. The emissions of SO_2 and dust are calculated from the monitoring report of the company.

$$\begin{aligned}&\text{Emissions(in kilogram)}\\&\quad = \text{Energy consumption (in terajoule)}\\&\qquad \times \text{Emission factor (in kilograms per terajoule)}\end{aligned} \tag{1}$$

Gasoline is locally produced in Changshu, which is where the company we investigated is located. We therefore neglect the transportation of gasoline and consider only the energy consumption and emissions regarding the production of gasoline; the corresponding factors are shown in Table 3 (Furuholt 1995). Because gasoline flows circularly through the pipeline, we assume that the singeing and stentering and setting stages require the same quantity of gasoline, and we allocate the impact of gasoline production to the two stages equally.

(b) Emissions from nonenergy use. This section includes the emissions of COD and suspended solid (SS). Based on the clean-production report of the company, the content of COD and SS before and after the wastewater treatment is shown in Table 4, and we use Eq. (2) to calculate the emissions.

$$E_{\mathrm{i}} = \frac{W \times C_{\mathrm{i}}}{1,000\rho} \tag{2}$$

where E_{i} refers to the emissions of i, in kilogram; W refers to the amounts of wastewater, in ton; C_{i} refers to the contents of i, in milligrams per liter; and ρ refers to the density of the wastewater. We assume the value is 1 kg/L, which is equal to the density of water.

For the amounts of wastewater, we assume that all of the additives except hydrogen peroxide are discharged directly into the wastewater. Hydrogen peroxide decomposes into oxygen and water. The oxygen is emitted into the atmosphere, and the water is discharged into the wastewater. With respect to the dyes, the fixation of reactive dyes is 70 % according to the literature (Gahr et al. 1994) and 75 % for threne dyes based on consultation with technicians. Therefore, 30 % of the reactive dyes and 25 % of the threne dyes are discharged into the wastewater. Moreover, the liquor retention value is 75 %, which means that the cotton fabrics absorb the liquid and are 75 % heavier during the dyeing process. When we dry the related cotton fabrics, we assume that this liquid evaporates. We use

Table 4 The contents of COD and SS before and after the wastewater treatment

	Before (mg/L)	After (mg/L)
COD	1,140	94
SS	122	54

Eq. (3) to calculate the wastewater emissions of each stage.

$$Q_W = Q_{RW} + Q_A + \frac{9}{17} Q_{HP} + 0.3Q_{RD} + 0.25Q_{TD} - 1,500n \quad (3)$$

where Q_W refers to the amount of wastewater emissions; Q_{RW} refers to the amount of river water; Q_A refers to the amount of auxiliaries, which does not include the amount of hydrogen peroxide; $9/17Q_{HP}$ refers to the amount of hydrogen peroxide that decomposes into water; $0.3Q_{RD}$ refers to the reactive dyes that are discharged into the wastewater; $0.25Q_{TD}$ refers to the threne dyes that are discharged into the wastewater; and $1,500n$ refers to the evaporation loss, where n refers to the number of times for drying and it is dimensionless. All the values in addition to n are expressed in units of kilogram.

(c) Emissions from transportation. This stage includes the transportation of cotton fabric, cotton thread, river water, additives, dyes, and coal. River water is obtained by the purification of water from the river next to the plant, and therefore, we exclude the transportation of river water. The cotton fabric needs to be treated in each part of the process; therefore, we allocate the impact of its transportation to each stage equally, except for the wastewater treatment stage. Data regarding the hauling distance and the vehicle type are provided by the company and are shown in Table 5. The emissions from the transportation correspond to the database of the GaBi version 4.3 software. The LCI of transportation and the cotton fabric dyeing process is shown in Table 6.

2. Final disposal. We considered two scenarios for the disposal of end-of-life cotton fabric, sanitary landfill, and incineration. Due to the uncertainty regarding the location where the final disposal would occur, we ignored transportation to a disposal site. The data are based on the waste treatment capacity of a city in China (Yang et al. 2002). Because of the lack of information, we ignored the energy consumption of the disposal stage and assume that the two scenarios are equal in proportion. The LCI of the final disposal process is shown in Table 7.

2.5 Impact assessment

We followed the CML2001 (CML2001, Dec.07, world) methods built into the GaBi 4.3 software for LCIA. Based on the results of LCI, the method of LCIA, and ISO 14040, we consider three main impact categories. The first impact category is total raw material or resource consumption, measured by abiotic depletion (ADP). The second impact category consists of atmosphere and water impacts. Atmospheric impacts are further divided into three subcategories, which include acidification potential (AP), global warming potential (GWP), and photochemical ozone creation potential (POCP). Water impacts are measured by eutrophication potential (EP). The third impact category is toxicity, which includes freshwater aquatic ecotoxicity (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity (MAETP), and terrestrial ecotoxicity potential (TETP).

3 Results

The LCI results of all of the impact categories are shown in Fig. 2, where the GWP, AP, POCP, and EP are the four major impacts. The values of the atmospheric impacts are larger than those of the others. However, the CML2001 method does not support weighting and aggregation into one score. Some smaller impact values may lead to serious consequences. We cannot ignore the impacts of the other categories. According to the previous introduction, the results of abiotic depletion, atmospheric impacts, water impacts, and toxicity are shown in Figs. 2, 3, 4, 5 and 6.

Table 5 Transportation data

Products	Origin	Vehicle type	Payload (t)	Distance (km)
Cotton fabric	75 % Jingzhou and 15 % Xuchang	Truck/euro 1	14–20	970
Cotton thread	Shanghai	Truck/euro 1	14–20	103
Softener	Yixing	Truck/euro 1	14–20	126
Chelate	Kunshan	Truck/euro 1	14–20	48.5
Penetrant	Kunshan	Truck/euro 1	14–20	48.5
Reactive dyes	Wuxi	Truck/euro 1	14–20	50.8
Threne dyes	Shanghai	Truck/euro 1	14–20	103
Other additives	Zhangjiagang	Truck/euro 1	14–20	42.7
Coal	Xuzhou	Motor ship/downstream	650	540

Table 6 The LCI of transportation and cotton fabric dyeing process

Category	Subcategory	Pretreatment									Dyeing		Finishing		Wastewater treatment
		Sewing	Cold pile	Desizing	Scour and oxygen bleaching	Singeing	Mercerizing	Brushing	Full-width washing	Baking	Reactive dyes	Threne dyes	Stentering and setting	Preshrinking	
Energy (MJ)	Electricity	0	82.9	200	523	98.8	530	706	310	99.4	449	507	967	47.6	1.33E+03
	Standard coal	0	0	0	1.96E+03	231	981	981	981	981	922	1.04E+03	872	0	0
	Raw coal	0	27.1	236	293	21.8	129	186	56.5	72.2	105	118	306	15.6	1.56E+03
	Washed coal	0	67.2	585	725	54	318	461	140	179	260	293	758	38.5	3.86E+03
	Fuel oil	0	0.579	5.04	6.25	0.465	2.74	3.97	1.21	1.54	2.24	2.52	6.53	0.332	33.3
	Crude oil	0	0.174	1.52	1.88	0.14	0.826	1.2	0.363	0.464	0.673	0.759	1.96	0.1	10
	Diesel	0	0.796	6.93	8.60	0.64	3.77	5.46	1.66	2.12	3.08	3.47	8.98	0.457	45.8
	Coke oven gas	0	1.06	9.24	11.5	0.853	5.03	7.29	2.21	2.83	4.1	4.63	12	0.609	61.1
	Natural gas	0	1.36E−02	0.118	0.147	1.09E−02	6.45E−02	9.34E−02	2.83E−02	3.62E−02	5.26E−02	5.93E−02	0.153	7.80E−03	0.782
	Steam	0	0	0	6.30E+07	0	3.15E+07	3.15E+07	3.15E+07	3.15E+07	2.96E+07	3.34E+07	0	0	0
	Gasoline	0	0	0	0	1.40E+03	0	0	0	0	0	0	1.40E+03	0	0
Material (kg)	Cotton thread	0.118	0	0	0	0	0	0	0	0	0	0	0	0	0
	Industrial salt	0	0	50	0	0	0	0	0	0	800	0	0	0	0
	Sodium carbonate	0	0	0	0	0	0	0	0	0	160	0	0	0	0
	LE-500	0	0	0	0	0	0	0	0	0	70	25	0	0	0
	Soaping agent	0	0	0	0	0	0	0	0	0	12	8	0	0	0
	Hydrogen peroxide	0	50	0	25	0	0	0	10.7	0	0	0	0	0	0
	Enzyme	0	83.3	13.3	0	0	0	0	0	0	0	0	0	0	0
	Stabilizer	0	54.2	0	26.7	0	0	0	10.9	0	0	0	0	0	0
	Penetrant	0	0	5	40	0	0	0	1.57	0	0	0	0	0	0
	Chelate	0	0	0	20	0	0	0	0	0	0	0	0	0	0
	Sodium hydroxide	0	0	0	183	0	3.36E−02	0	0	0	0	250	0	0	0
	Rongalite	0	0	0	0	0	0	0	0	0	0	100	0	0	0
	Sulfuric acid	0	0	0	0	0	14.4	0	0	0	0	0	0	0	0
	Glacial acetic acid	0	0	0	0	0	11.1	0	0	0	0	0	0	0	0
	Softener	0	0	0	0	0	0	69.8	0	0	0	0	250	0	0
	Reactive dyes	0	0	0	0	0	0	0	0	0	114	0	0	0	0
	Threne dyes	0	0	0	0	0	0	0	0	0	0	63.1	0	0	0
	River water	0	5.16E+03	3.19E+04	3.45E+04	5.96E+03	1.25E+04	0	2.03E+04	0	5.21E+04	4.13E+04	3.10E+03	0	0

Table 6 (continued)

Category	Subcategory	Pretreatment									Dyeing		Finishing		Wastewater treatment
		Sewing	Cold pile	Desizing	Scour and oxygen bleaching	Singeing	Mercerizing	Brushing	Full-width washing	Baking	Reactive dyes	Threne dyes	Stentering and setting	Preshrinking	
	Water	0	1.29	3.13	4.60E+03	5.41E+02	2.30E+03	0	2.30E+03	2.30E+03	2.16E+03	2.44E+03	555	0.742	20.7
Emissions to air (kg)	CO_2	11.4	28	64.9	5.52E+03	670	2.85E+03	2.90E+03	2.78E+03	2.79E+03	2.67E+03	3.01E+03	947	16.3	420
	CO	2.63E−02	6.78E−02	0.158	0.279	7.14E−02	0.347	0.484	0.177	0.214	0.323	0.357	0.739	3.93E−02	1.02
	SO_2	3.58E−04	2.38E−02	5.75E−02	4.15	4.71	2.15	2.2	2.09	2.1	2.01	2.26	4.96	1.37E−02	0.38
	CH_4	2.32E−04	3.53E−05	2.81E−05	27.2	3.2	13.6	13.6	13.6	13.6	12.8	14.4	3.2	2.39E−05	0
	NO_x	0.116	0.138	0.305	0.585	0.144	0.684	0.945	0.365	0.434	0.723	0.784	1.436	8.09E−02	1.92
	N_2O	2.17E−04	3.30E−05	2.63E−05	8.62E−02	0.133	4.31E−02	4.31E−02	4.31E−02	4.31E−02	4.08E−02	4.60E−02	1.02E−02	2.23E−05	0
	Dust	4.83E−03	0.221	0.532	0.867	0.201	1.15	1.61	0.562	0.689	0.954	1.07	2.51	0.13	3.51
	Ammonia	8.35E−05	1.27E−05	1.01E−05	1.53E−05	8.60E−06	0.000	1.31E−05	9.11E−06	8.60E−06	1.17E−04	1.09E−04	2.49E−05	8.60E−06	0
	Group NMVOC	9.42E−03	1.44E−03	1.14E−03	8.25E−03	1.74E−03	4.30E−03	4.74E−03	4.29E-03	4.23E−03	1.62E−02	1.58E−02	3.57E−03	9.70E−04	0
Emissions to water (kg)	Wastewater	0	3.83E+03	3.20E+04	3.18E+04	4.46E+03	1.10E+04	1.45E+03	1.88E+04	0	5.42E+04	4.29E+04	1.85E+03	0	0
	COD	0	4.36	36.5	36.2	5.08	12.6	1.67	21.4	1.72E−02	61.8	48.9	2.12	4.11E−04	−212
	SS	0	0.471	3.92	3.93	0.552	1.39	0.23	2.32	3.40E−02	6.65	5.28	0.282	2.61E−03	−13.7
	VOC	0	0	0	0	0.265	0	0	0	0	0	0	0.265	0	0
	Pb^{2+}	0	2.13E−06	5.15E−06	6.39E−06	1.71E−06	1.01E−05	1.46E−05	4.44E−06	5.67E−06	8.24E−06	9.29E−06	2.40E−05	1.22E−06	3.41E−05
	Hg^{2+}	0	4.48E−08	1.08E−07	1.34E−07	3.60E−08	2.12E−07	3.07E−07	9.32E−08	1.19E−07	1.73E−07	1.95E−07	5.05E−07	2.57E−08	7.16E−07
	F^-	0	4.03E−07	9.74E−07	1.21E−06	3.24E−07	1.91E−06	2.77E−06	8.39E−07	1.07E−06	1.56E−06	1.76E−06	4.55E−06	2.31E−07	6.44E−06
	Cd^{2+}	0	7.90E−08	1.91E−07	2.37E−07	6.35E−08	3.75E−07	5.43E−07	1.65E−07	2.10E−07	3.06E−07	3.45E−07	8.91E−07	4.53E−08	1.26E−06
	Arsenic	0	1.82E−06	4.41E−06	5.47E−06	1.47E−06	8.65E−06	1.25E−05	3.80E−06	4.86E−06	7.05E−06	7.95E−06	2.06E−05	1.05E−06	2.92E−05

NMVOC nonmethane volatile organic compounds

Table 7 The LCI of the final disposal process

Emissions		Sanitary landfill (kg)	Incineration (kg)
Emissions to air	CO	0.204	0.578
	CO_2	120	722
	CH_4	26.3	0
	N_2O	0	0.123
	Chlorinated hydrocarbons	2.79E−03	9.02E−02
	NOx	0.235	0.513
	SO_2	0.275	1.03
	HCl	5.23E−03	0.225
	H_2S	1.34E−02	1.75E−05
	NH_3	4.61E−07	8.40E−05
Emissions to water	COD	6.41E−02	2.81E−03
	Cd	6.31E−07	0.451
	Pb	2.87E−06	5.65E−03
	Hg	0.270	0.458

3.1 Abiotic depletion

The normalized ADP potential of each process and stage is reported in Fig. 3. The wastewater treatment contributes the largest ADP potential because the wastewater treatment stage requires many types of blowers for aeration and ventilation. The wastewater treatment stage consumes a large amount of electricity during the operation of the blowers. Meanwhile, the stentering and setting stage contributes a large ADP potential also because of the amount of electricity consumed. Reactive dyes and threne dyes contribute similar ADP potentials because of the similar consumption of electricity and steam; however, the threne dye values are slightly greater.

3.2 Atmosphere impacts

The normalized emission potential value for each stage is very small and varies greatly; thus, it will not be possible to

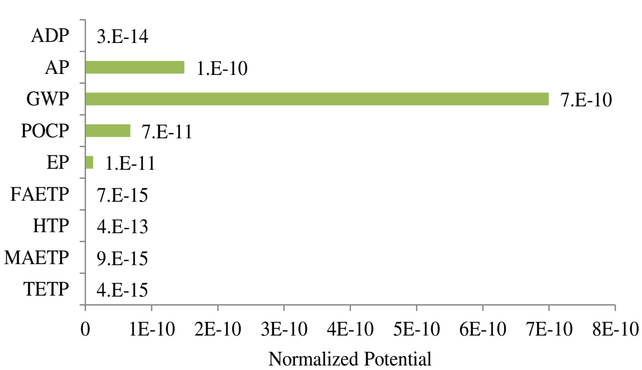


Fig. 2 Normalization results of all the impact categories

demonstrate and compare the whole stage in one figure. Therefore, we create Eq. (4) to solve the problem:

$$E' = -lgE \tag{4}$$

where E' refers to the normalized emission potential value that can be demonstrated and compared easily and E means the initial normalized emission potential value.

After such a process, when E' is higher, the corresponding air emission potential is lower. Figure 4 shows the results for the treated normalized emission potential. For AP, the impact potential of stentering and setting is the largest while that of preshrinking is the lowest of all of the stages. The stentering and setting stage requires gasoline heating to generate high temperatures, which will generate extensive amounts of SO_2 and NOx. Preshrinking needs only electricity and excludes the transportation process; therefore, preshrinking produces lower air emissions, which are related to high AP. For GWP, scouring and oxygen bleaching provides the largest potential, while sewing provides the lowest. For POCP, the largest and the lowest potentials of all the stages are provided by scouring and oxygen bleaching and preshrinking, respectively. Reactive and threne dyes generate similar air emissions potentials, as do sanitary landfill and incineration. The performance of sanitary landfill is slightly worse than that of incineration, except with regard to the AP potential. All of these consequences can be attributed to the differences in energy consumption and emissions during the production, transportation, and disposal throughout all of the stages.

3.3 Water impacts

The normalized EP potential of each stage is shown in Fig. 5. The wastewater treatment process efficiently reduces the COD such that the net EP potential is negative. The impact of the reactive dyes is the largest, followed by that of the threne dyes. At the same time, the desizing and scouring and oxygen bleaching stages also contribute a large EP potential. These consequences are mainly due to the large amount of COD emissions generated during these stages. With regard to the two scenarios of final disposal, sanitary landfill is better than incineration.

3.4 Toxicity

The normalized toxicity potential is shown in Fig. 6. For FAETP and TETP, stentering and setting contributes the largest potential. For MAETP, wastewater treatment

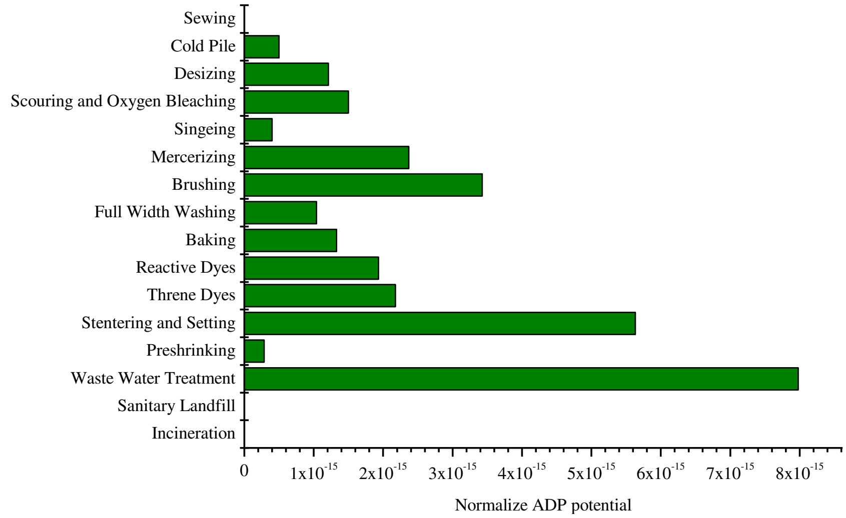


Fig. 3 Normalized ADP potential of each stage

performs the worst. The stentering and setting and wastewater treatment stages consume large amounts of electricity and will generate heavy metal discharge during the production process. The toxicity potential is therefore higher for these two stages. For HTP, incineration contributes nearly all of the potential due to the large amount of air emissions in this stage. There is a minor difference between the reactive and threne dyes.

4 Discussion

4.1 Comparison of results

Many studies show that wastewater is the largest waste stream for all subsectors of the textile industry. Understanding how to reduce the use of water and water impacts is the key to sustainable development in the dyeing industry (Xie et al. 2011; Bechtold and Turcanu 2009; Xie et al. 2009; SEAM Programme 2004). However, in our research, atmospheric impacts, especially GWP, exhibit the poorest performance among all of the environmental categories based on normalized results. According to the environmental impact report obtained from the company, the desizing, and scouring and oxygen bleaching stages are the key processes. The results of this study show that the scouring and oxygen bleaching, dyeing, and stentering and setting stages are the key processes. The differences of previous studies with our research may be resulted from too much emphasis on the impact of the water system while ignoring the other aspects. Besides, our study does not consider possible impacts from water emissions of dyes and additives which may contribute significantly. Finally, the lack of research on the dyeing process from the life-cycle perspective leads to the neglect of environmental

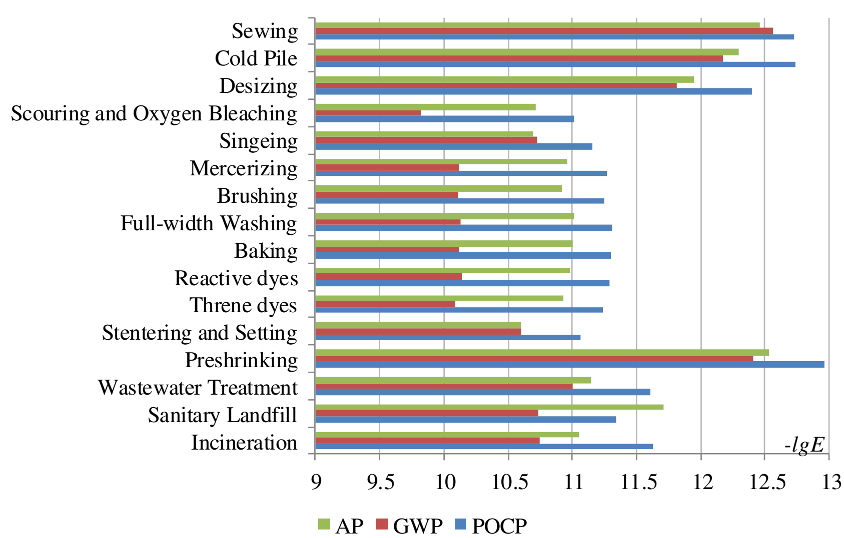


Fig. 4 Treated normalized air emissions potential of each stage

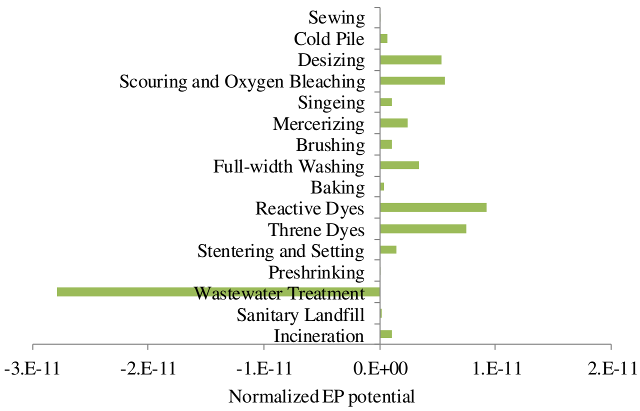


Fig. 5 Normalized EP potential of each stage

impacts of energy production, raw material transportation, final disposal, and the other processes.

4.2 Feasible cleaner production proposal

From the previous analysis, of all of the processes, scouring and oxygen bleaching, dyeing, stentering and setting, wastewater treatment, and incineration are crucial for cleaner production because of the large amount of energy and resources consumed during production and transportation as well as the emissions generated during each of the above processes. We should therefore reduce the pollution due to these processes.

For the production process, the core solutions involve controlling the consumption of energy and resources as well as enhancing the recycling of energy and resources. The following measures in particular will be useful. First, the recycling of water is to be enhanced, including the cooling water of the singeing stage and the process water of the scouring and oxygen bleaching and mercerizing stages (Kiran-Ciliz 2003). Second, the consumption of additives and dyes is to be controlled through appropriate order scheduling (Sun et al. 2010) and the usage of dyes with a high level of fixation. Third, as much energy is to be saved as possible. According to the Natural Resources Defense Council (NRDC), we could reuse the heat generated by flue and hot water; prescreen the coal; increase the utilization rate of equipment; increase the adiabatic treatment of pipelines, valves, and flanges; and examine the steam trap regularly (Greer et al. 2010).

Our study includes two types of vehicles, trucks and motorized shipping. To reduce the impact of the transportation process, we compare the impacts of different vehicle types and distance with the help of the GaBi version 4.3 software. The scenarios considered are shown in Table 8, and the results are shown in Table 9.

The performance of the motorized shipping is better than that of the trucks, regardless of the distance. When we choose the vehicle type, when conditions permit, we should give priority to the use of motorized shipping by water to reduce the life-cycle environmental impact.

4.3 Uncertainties and outlook

The uncertainties in our research occur mainly in the area of data quality and evaluation methodology as well as temporal and spatial variation. There are three types of uncertainty that affect data quality. Some data are obtained from the monitor report and allocate the emissions according to daily outputs, such as the emissions of SO_2, while others allocate to each stage proportionally, such as the consumption of steam. Some types of data, such as COD and SS, still incorporate uncertainties. Much work remains to improve the quality of the data. We chose the CML2001 method built into the GaBi version 4.3 databases as the evaluation methodology, but there are some limitations to the method itself. The CML2001 models the impacts at a midpoint

Fig. 6 Normalized toxicity potential of each stage

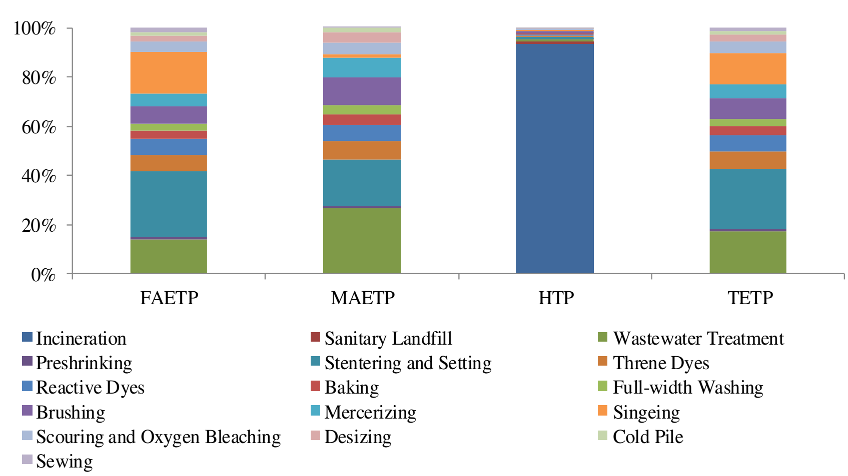


Table 8 Different scenarios for transportation

Scenarios	Vehicle type	Load (t)	Cargo (t)	Distance (km)
A	Truck/euro 1	14–20	1	100
B	Truck/euro 1	14–20	1	300
C	Truck/euro 1	14–20	1	500
D	Motorized Ship/downstream	650	1	100
E	Motorized Ship/downstream	650	1	300
F	Motorized Ship/downstream	650	1	500

somewhere in the environmental mechanism between emissions and damages and reduces the number of assumptions as well as the complexity of the model such that it is easy to operate (Dreyer et al. 2003). However, it will be difficult to determine the ecotoxicity of some chemical substances, such as the dyes and additives, leading to uncertainty in the evaluation results. CML2001 does not support weighting and aggregation into single-score results. It will therefore be difficult to compare the impacts between different categories. For temporal and spatial variation, we considered only two scenarios for final disposal, used the Chinese wastewater data, and ignored the technical changes.

In sum, in the future, it will be necessary to study the uncertainty in the LCI data (Sonnemann et al. 2003), in terms of the evaluation methodology as well as the temporal and spatial variation. Moreover, the products we studied will be further processed into clothes, sofa covers, and other products in different countries. This further processing may require the use of water, detergents, and electricity during the ultimate use of the final products. However, this use may not occur in the same country of initial production. From a consumption-based perspective, we could discuss the allocation of responsibility among different countries if we have sufficient information and data (Larsen and Hertwich 2009). Some scholars have shown that the dyes of reactive flavine are the highest in toxicity (Huang and Luo 2001). It will be necessary to compare the relative toxicities of dyes and additives if we have the normalized factor from CML2001. At the same time, the further development of weighting methods would be useful (Finnveden et al. 2009). Besides, we only considered the metal water emissions. It will be necessary to include the contribution of metal air emissions in our further studies.

4.4 Innovation

The innovative aspect of our program is the comprehensive analysis of the environmental impacts of wet processing from a new life-cycle perspective. These findings will promote cleaner production throughout the entire textile-dyeing industry.

5 Conclusions

GWP, AP, POCP, and EP are the four major impacts, and the scouring and oxygen bleaching, dyeing, stentering and setting, wastewater treatment, and incineration stages are the critical stages to consider achieving cleaner production. Some measures should be taken to reduce the environmental impacts of these key processes. First of all, the recycling of water should be enhanced; this includes recycling cooling and process water. Second, the consumption of additives and dyes should be controlled through order scheduling and the utilization of dyes with high fixation. Third, the advice of the NRDC should be implemented and as much energy as possible

Table 9 The results of the transportation scenarios

Scenarios	AP	EP	FAETP	GWP	HTP	MAETP	POCP	TETP
A	2.12E−13	5.96E−14	8.07E−17	1.69E−13	7.67E−15	2.88E−19	1.15E−13	2.93E−17
D	2.40E−14	6.28E−15	8.79E−18	9.70E−15	2.56E−16	3.12E−20	1.24E−14	3.18E−18
B	6.37E−13	1.79E−13	2.42E−16	5.08E−13	2.30E−14	8.65E−19	3.45E−13	8.78E−17
E	7.19E−14	1.88E−14	2.64E−17	2.91E−14	7.68E−16	9.36E−20	3.72E−14	9.55E−18
C	1.06E−12	2.98E−13	4.04E−16	8.46E−13	3.84E−14	1.44E−18	5.75E−13	1.46E−16
F	1.20E−13	3.14E−14	4.39E−17	4.85E−14	1.28E−15	1.56E−19	6.21E−14	1.59E−17

should be saved. To reduce the environmental impacts of the transportation process, when conditions permit, we should give priority to motorized shipping instead of trucks. Finally, additional work should be performed on the following: considering a consumption-based perspective of the entire process, the uncertainty in the LCI data, the evaluation methodology and the temporal and spatial variation, and the normalized toxicity of dyes and additives as well as the weighting methods.

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